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Frequency control and pre-tuning of a large aperture 500 MHz 5-cell superconducting RF cavity

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The 500 MHz 5-cell superconducting RF (SRF) cavity was designed aiming to be a candidate cavity for high current accelerators. A copper prototype cavity and a niobium cavity were fabricated at SINAP in 2012. In order to ensure these cavities get the desired frequency and a good field flatness higher than 98%, frequency control was implemented in the manufacturing process and pre-tuning has been done using a simple pre-tuning frame based on the bead-pull pre-tuning method. Then, TM_{010}-π mode frequency within 5 kHz from the target frequency was achieved and the field flatness reached 98.9% on the copper prototype cavity. Finally, the same procedure was applied to the niobium cavity to obtain a field flatness better than 98% which benefited the cavity performance in the vertical testing.

Keywords: Superconducting RF cavity, Frequency control, Pre-tuning, Field flatness, Bead-pull method

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I. INTRODUCTION

For a multi-cell superconducting RF (SRF) cavity, the cells differ a little from each other in the shape owing to machining errors in their deep-drawing, hence the cavity's resonant frequency deviation from the design, and different amplitudes of the accelerating electric field in the cells. This may cause many problems: the accelerating electric field E_{acc} cannot be maximized, and the peak surface EM fields E_{peak} and B_{peak} cannot be minimized. These can be tackled with frequency control in the whole process and eventual pre-tuning procedure.

Frequency control is an essential part in producing an SRF cavity. Pre-tuning of the cavity can regulate the resonant frequency and field strength distribution of the cavity [1]. It is an effective way to obtain a uniform and perfect field of the cavity and make it resonate at a desired frequency. The bead-pull method is a widely adopted way of pre-tuning SRF cavities of different kinds [2–4].

The resonant frequency of the 500 MHz 5-cell SRF cavity is lower than those of the 700 MHz and 1.3 GHz cavities. This means lower BCS surface resistance at the same temperature, larger aperture and longer accelerating gap. It is advantageous in its low cryogenic heat load, low power of high-order modes and high threshold current for accelerators, making it a possible candidate cavity for high current and compact linacs. However, there are also many challenges in fabricating and pre-tuning the large size cavity.

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II. FREQUENCY CONTROL

The operating frequency of the 5-cell SRF cavity is 499.65 MHz at 4.2 K. The cavity shapes and length will definitely determine the its frequency and affect partially its assembly to the cryostat. Thus, the frequency has to be precisely controlled in the whole procedure of manufacturing, including trimming, electron beam welding (EBW), mechanical barrel polishing, buffered chemical polishing (BCP) etc.

For the 500 MHz 5-cell cavity [5], according to our experience in developing a 500 MHz single-cell cavity, the TM_{010}-π mode frequency at room temperature after EBW should be 498.8 MHz so as to reach 499.65 MHz after assembling to the cryostat. A straight section on equator the single-cell could be adjusted to tune the frequency. CST simulation results showed that the TM_{010}-0 mode frequency had the same variation as the TM_{010}-π mode (Fig. 1). Therefore, we used a simple method to control TM_{010}-π mode frequency: controlling the TM_{010}-0 mode frequency. The frequency measurement was carried out on two assembled half-cells instead of an EBW dumbbell cell. The straight section on the end cell was changed in length to regulate the field flatness. The EBW copper cavity had a TM_{010}-π mode frequency of 497.62 MHz and field flatness of (91.7 ± 0.6)% before pre-tuning. The frequency deviation from target value was within 1.2 MHz, which was corrected in the latter pre-tuning process.

III. PRE-TUNING

A. Review on pre-tuning theory

The first thing of pre-tuning is to calculate the field flatness and the frequencies needed to tune each cell. When a metal bead passing through the axis of a cavity, the TM_{010}-π mode electric field shall be [6]

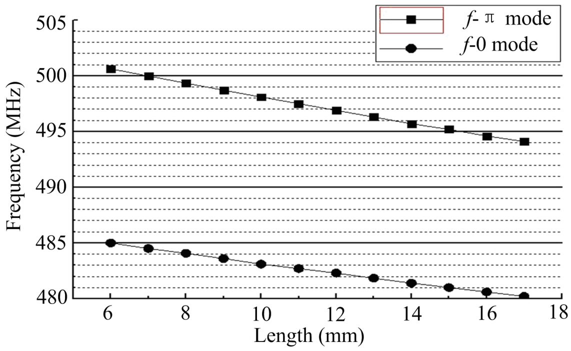

Fig. 1. Resonant frequency versus the length of the straight segment on the cell equator.

$$E^2 \propto \Delta f \propto \begin{cases} \tan(\Delta\varphi), \\ \dfrac{1}{Q_L}, \end{cases} \tag{1}$$

where $\Delta\varphi$ is the phase shift of S_{21} and Δf is TM_{010}-π mode frequency excursion of the cavity. By measuring Q_L and $(\Delta\varphi_{\max})_i$ ($i = 1, 2, \ldots, N$, is the cell number), one obtains the maximum phase shift of Cell i, $(\Delta f_{\max})_i$ and the relative $(E_{\max})_i$. Substituting $(E_{\max})_i$ into Eq. (2) to calculate the field flatness

$$ff = \frac{\frac{1}{N}\sum_{i=1}^{N}(E_{\max})_i}{E_{\max}} \times 100\%. \tag{2}$$

The frequencies needed to tune each cell [7] can be calculated by Eq. (3)

$$(\Delta f_{\text{tune}})_i = \Delta f^{\pi} + (\Delta f_{\text{c}})_i, \tag{3}$$

where $\Delta f_{\text{tune}} = (f^{\pi}_{\text{desired}} - f^{\pi}_{\text{measured}})/N$, f^{π}_{desired} and $f^{\pi}_{\text{measured}}$ are the desired and measured frequency of the TM_{010}-π mode, respectively, and $(\Delta f_{\text{c}})_i$ is related to $f^{i\pi/N}_{\text{measured}}$ and $(\Delta f_{\max})_i$.

Pre-tuning a cell is a physical procedure: axially squeezing or stretching the cells to be tuned. Squeezing a cell lowers its resonant frequency, while stretching a cell increases its resonant frequency. So by pushing or pulling cells, the resonant frequency can be tuned to the desired frequency and a good field distribution can be obtained.

B. Establishing pre-tuning frame

A pre-tuning frame based on the bead-pull method was applied to pre-tune the 500 MHz 5-cell cavity. Fig. 2 is the schematics, which includes the data acquisition of field distribution and cavity frequency tuning. The hardware (Fig. 3) contains a perturbation bead, a computer, a vector network analyzer (VNA), a step motor and its controller, etc. The software is a LabVIEW and MATLAB hybrid codes. The LabVIEW code is performed for data acquisition between the VNA and the computer, and for the step motor control. The MATLAB code is used for calculation. In this pre-tuning frame, the VNA is set to work in the continuous wave mode [8] at the unperturbed TM_{010}-π mode frequency, and the step motor is set to move at a constant speed so that the perturbation bead pass through each cell in a uniform manner in fixed frequency. The phase shift when the bead pass through each cell is obtained from S_{21} curve.

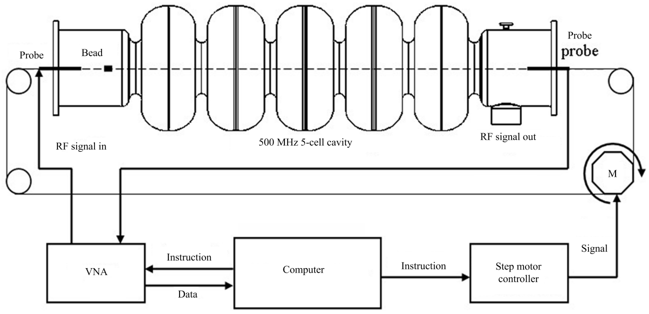

Fig. 2. Schematics of bead-pull pre-tuning apparatus at SINAP.

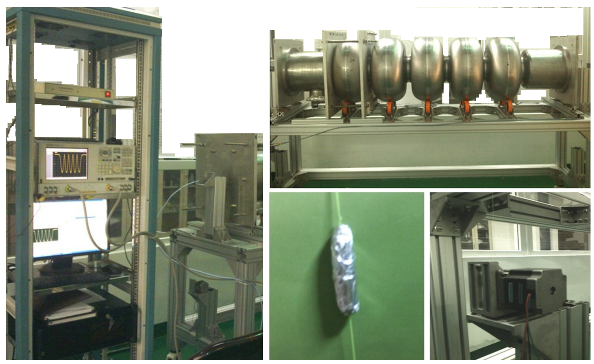

Fig. 3. (Color online) Bead-pull pre-tuning frame at SINAP.

C. Pre-tuning of the copper prototype cavity

Before making the niobium cavity, a copper prototype cavity was built to explore the fabrication procedures and develop the measurement techniques. The pre-tuning process executed on the Cu cavity showed that the $f^{\pi}_{\text{measured}}$ was 497.618 MHz, and the reasonant frequencies of Cells 1, 2, 3, 4 and 5 were lower than the target frequency by 0.181 MHz, 0.271 MHz, 0.256 MHz, 0.297 MHz and 0.163 MHz, respectively. With frequency control, the field flatness of the copper cavity reached $(91.7 \pm 0.6)\%$ and frequency deviation from target was 1.2 MHz. The strong cell-to-cell coupling ($k_{\text{cc}} = 3.18\%$) due to the cavity's large aperture, and the deep-drawing technology employed also played an important role.

Regulating cell by cell is an easy approach for pre-tuning [8, 9]. For the 500 MHz 5-cell copper cavity, Cells 2, 3 and 4 were close to each other in Δf_{tune}, with a differences of just 0.041 MHz, while Cells 1 and 5 were over 0.1 MHz less in Δf_{tune} than other cells. We attempted to tune the cavity in two methods. One was to squeeze Cells 1 and 5 to enlarge their Δf_{tune} to 0.27 MHz, so as to get a field flatness better than 98%, followed by stretching the whole cavity to increase the TM_{010}-π mode frequency to 498.8 MHz. However, after 600 °C annealing, the copper cavity was very soft. When stretching the whole cavity, deformation occurred on Cells 1 and 5, and the field flatness decreased to about 92%.

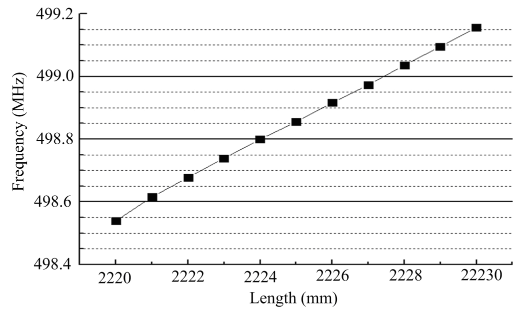

Fig. 4. $TM_{010} - \pi$ mode frequency vs total length of the cavity.

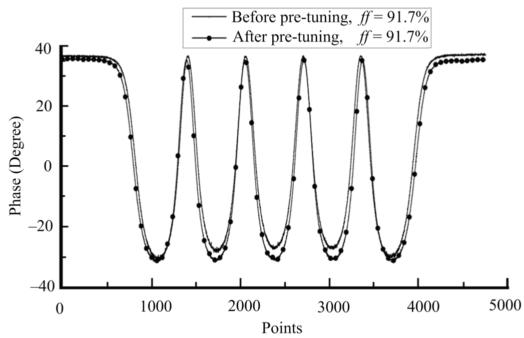

Fig. 5. Field distribution of the copper cavity before pre-tuning and after pre-tuning.

The second way was to pull the whole cavity from 2221 mm to 2229 mm to reach 499.1 MHz, which is a little higher than the desired frequency (Fig. 4), followed by pushing Cells 1 and 5 to tune frequency to 498.8 MHz and to acquire a field flatness better than 98%. The field flatness of 98.9% was achieved and the TM_{010}-π mode frequency was tuned to 498.798 MHz, being just 2 kHz lower than the desired frequency. The electric field distribution profile in Fig. 5 was uniform, a nice field in good accordance with the simulation results [5]. After pre-tuning, the total length of the copper cavity returned back to 2224 µm. The 5 modes frequencies of TM_{010} measured by VNA after pre-tuning were given in Table 1.

Tabelle 1. TM_{010} mode frequency of the copper cavity after pre-tuning

Modes	Frequency (MHz)
$\pi/5$	485.023
$2\pi/5$	488.592
$3\pi/5$	493.263
$4\pi/5$	497.256
π	498.798

D. Pre-tuning of the niobium cavity

Pre-tuning consequences of the copper cavity laid a solid foundation for pre-tuning the niobium cavity. For the 500 MHz 5-cell niobium cavity before pre-tuning, the $f^{\pi}_{\text{measured}}$ was 497.754 MHz, the reasonant frequencies of Cells 1, 2, 3, 4 and 5 were 0.131 MHz, 0.241 MHz, 0.223 MHz, 0.221 MHz and 0.225 MHz lower than the target frequency, respectively, and the field flatness was just 78.6%. It was pre-tuned in the similar way as the copper cavity. However, after 680 °C annealing, the niobium cavity was still of high hardness. It was difficult to obtain plastic deformation by manual squeezing or expanding. So we decided to squeeze just Cell 1 to get good field flatness and abandon the frequency adjustment. The tuning process is shown in Fig. 6. Eventually, the field flatness was tuned to 98.5%, and the $TM_{010} - \pi$ mode frequency was 497.728 MHz, i.e. 1.1 MHz lower than the desired frequency.

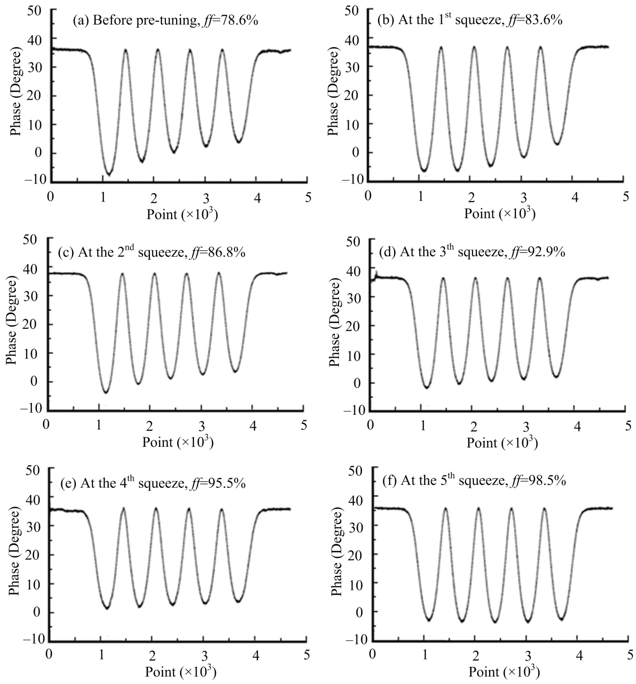

Fig. 6. Pre-tuning process of the 500 MHz 5-cell niobium cavity, by squeezing just Cell 1.

After pre-tuning, vertical testing was done on the niobium cavity on December 17, 2012. A good result, V_{acc} =

$7.5\,\mathrm{MV@Q_0} = 1 \times 10^9$, was achieved. The $\mathrm{TM_{010}}$-π mode frequency was approximate $498.3\,\mathrm{MHz}$ at $4.2\,\mathrm{K}$.

IV. CONCLUSION

A large aperture $500\,\mathrm{MHz}$ 5-cell SRF cavity was designed and fabricated at SINAP. From the beginning, frequency control was taken into consideration, which guaranteed that the EBW cavity had a frequency deviation of less than $1.2\,\mathrm{MHz}$. Both the copper prototype cavity and the niobium cavity were pre-tuned on the established apparatus. The field flatness reached better than 98%, which was only 78% before pre-tuning of the niobium cavity. The frequency control and pre-tuning helped to ensure the cavity's final vertical testing performance.

[1] Sun A, Wang H P, Wu G F. in Proc. LINAC 2004, Lübeck, Germany.
[2] Furuta F, Saito K. in Proc. SRF 2009, Berlin, Germany.
[3] Zhang H, Yang L, Wang F, *et al*. Nucl Electron Detect Technol, 2012, **32**, 1:7-10.
[4] Hartung W, Compton C C, Grimm T L, *et al*. Status Report on Multi-cell Superconducting Cavity Development for Medium-velocity beams. in Proc. Particle Accelerator Conference, 2003, Portland, USA.
[5] Wei Y L, Liu J F, Hou H T, *et al*. Nucl Sci Tech, 2012, **23**: 257–260.
[6] Christopher C. Single Iteration Tuning for Multicell RF Cavities for Cornell ERL. Cornell University, Ithaca, NY, 14853. (Dated: August 8, 2003)
[7] Hasan P, Jens K, Tom H. RF Superconductivity for Accelerators. NewYork. A Wiely-Interscience Publication, 1998. 129–144.
[8] Guo Z D, Li Z Q, Zhai J Y, *et al*. High Power Laser Particle Beams, 2011, **23**, 175–178. (in Chinese)
[9] Shishido T, Kako E, Noguchi S. Development of Pre-tuning System for 972 MHz 9-cell Superconducting Cavities. Submitted to the 11th Workshop on RF Superconductivity (SRF2003), September 8-12, 2003. (Luebeck/Travemuende, Germany)